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Novel WSN Hardware for Long Range Low Power Monitoring

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***Abstract*—Environmental monitoring applications often require 24/7 operation in harsh, low resource (e.g. power and communication) environments over a large scale area with ad-hoc deployment of sensors. Data processing at the sensor is required to minimize communication overhead. Such an application scenario presents opportunities for research in wireless sensor networks (WSN)s that are distinct from existing commercial off-the-shelf (COTS) solutions. We present a novel modular, highly flexible, hardware solution with a core feature of a System on a Chip (SoC) with add-ons such as memories, interfaces, and different transmission input/output I/O modalities. The system can manage, process, and transmit data directly within an ad-hoc self healing, self forming, mesh network over long distance (19 km between nodes in the current implementation) or as a stand-alone system. Hardware has been produced and the system has been validated in real-world deployments.**

***Keywords*-self-healing; self-forming; WSN hardware; environmental monitoring; low power; long range**

I. Introduction/Motivations

Interest in wireless mesh networks has been driven largely by improving the last mile of internet access and developing the Internet-Of-Things. There is a large body of research and commercially available sensor motes have been developed with a variety of sensor types that are sold with communication capabilities including Bluetooth, RFID, radio (400 MHz up to 2.4 GHz), and GSM. Some common examples of such sensor nodes include the Waspmote sensor node, MICA2 sensor node, and Telos/Tmote. These solutions generally do not meet the unique needs of environmental monitoring applications that frequently are in remote environments, outside the range of cellular connectivity or power lines, over a very large area using sensors placed kilometers apart. As a result, typically conventional environmental sensors are connected in a wired array and data is stored to a local hard drive. Data retrieval is often manual, requiring a field campaign that can last days. On-site damage can occur and valuable stored data could be lost. Manual data retrieval makes data management and distribution difficult.

To address these shortcomings, LANL designed a novel modular hardware solution called the Remote Terminal Unit (RTU) (submitted for full US patent April 27, 2016). A core feature of the RTU is its highly flexible design with add-ons such as memories, interfaces, and different transmission input/output modalities. The system can manage, process, and transmit data directly within an ad hoc mesh or as a stand-alone system via a satellite modem. The board can be adapted at install time to the power and communication requirements of different systems. This allows for the optimization of the network to various applications and evolving requirements. The system, scalable to hundreds of nodes, was designed so that nodes can be placed 19 km apart line of sight, yet can effectively communicate between large subgroups of nodes in close proximity to each other, configurable to balance communication priorities with efficiency.

System metrics include: node count (3-1000+); node-node distance (5 m - 20+ km); electrical power, processing capability, and network protocol. The difficulty witfh research in this areas is that real-world implementations are typically limited in scope and actual performance can be quite different from simulations or small pilot demonstrations.

II. Related Work

Extensive research in WSNs has refsulted in numerous hardware configurations and networking algorithms with simulated results. Real-world implementations are very limited in number and the scope and actual performance are quite different. Mid and Long distance communication between two sensor nodes are demonstrated as feasible. For example [8] demonstrates a 12 km communication using a waspmote sensor node and [2] manages 350 meter communication despite using a 2.4 GHz communication channel. However, these studies did not implement these communications in a sensor network.

The most notable examples of deployed multi-hop networks with *long-range radios* found in the literature are: a 6 node self-healing network with wireless connections over 10 km in distance, with the longest connection being 23 km, utilizing the commercially available 9-XTend radio [1]; and an 11 node network with line of sight (LOS) connections over distances as long as 17.7 km also using the 9-XTend radio [7]. [5] describes communication over distances as great as 2.5 km in a 10 node sensor network, and [4] describes a 4 node network that manages distances up to 1.8 km. [6] describes a 20 node network with some nodes communicating over distances of approximately 1 km.

The sensor network we present in this paper is unique with regard to its combination of long distance links, high node count, low power, and application versatility. Though many of the previous efforts demonstrate some of these qualities individually, to our knowledge there is no published work detailing an RF self-healing mesh sensor network with node-to-node distances as large as 19 km and with a node count as large as 62 nodes. Additionally, our board's power consumption compares well to that of other long distance node systems.

III. Network Requirements

The sensor network system architecture is shown in Figure 1. Any sensor node in the network can be a "master" node for data transmission, a "relay" node or a "sensor" node. The "master" node collects data from several or all nodes in the network and organizes the data into packets for data transmission via satellite or directly to a local server. A relay node sends sensor data to another node in the network. A "sensor" node collects raw sensor data, either digital or analog, and has the ability to process the raw data according to application requirements and transmit the data to the "master" node in the network (and/or to a remote server via satellite). Each sensor node has dual function for data transmission, i.e., line-of-sight RF and/or satellite. Data transmission within the sensor network system on the ground is implemented by a line-of-sight radio. Data transmission to a remote server from any node is implemented with a 2-way SBD RockBLOCK terminal (Iridium 9602 modem). The application specific data transmission method is configured at field installation time due to the nature for the terrain and the complexity of distance between nodes.

Often RTU monitoring applications have low average sensor data rates with infrequent "event" information. The event interval may be as little as a few minutes or as long as once in a 6 month period. However, event messages require close to 100% reliability, i.e. no missed events that must be reported within a half hour to one hour from the event detection. The network can be sparse in certain localities with marginal communication links due to geological and/or environmental interference while at the same time some fraction of the nodes are tightly clustered together. Still others, have a significant mountain range in between them and the mesh, thus, dual modality for data transmission was a requirement as all nodes cannot reach the mesh and some must be treated independently.

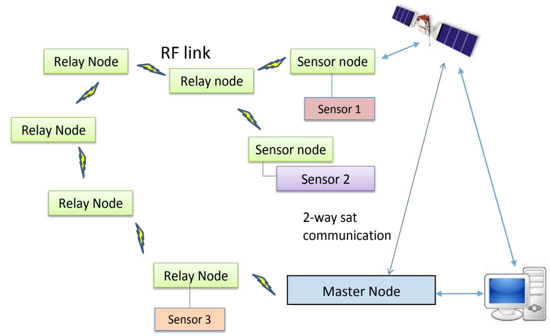

Figure 1. Sensor System Architecture

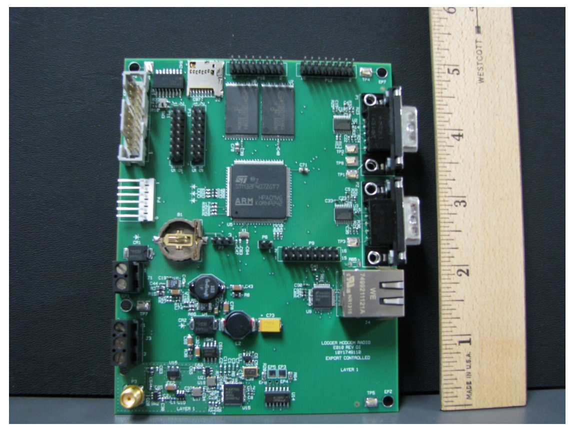

Figure 2. Image of the Remote Terminal Unit (RTU). A ruler is shown for scale.

To address these networking constraints, we use a self-configuring, adaptive tree based protocol. Unlike tree based protocols such as CTP [3], we do not continuously maintain a path between nodes to the base station. Instead, we periodically refresh the tree from the base station. This is done because events are quite rare and unpredictable in our application scenario. Data is acknowledged at each hop on the route to the base station and re-transmitted 10 times if an acknowledgement is not received. Nodes maintain the quality of links to their parents by keeping track of the number of re-transmissions. At each refresh interval, the best available parent is chosen based on a combination of the number of hops and the link quality. The system will be deployed and tested at scales of 200 nodes later this year.

IV. Hardware Description

An image of the RTU can be seen in Figure 2. The SoC is central to its low power consumption, programmer friendliness, and computational ability. We use an ST Microelectronics^{TM} advanced RISC machine (ARM) M4 cortex processor (STM32F407ZGT6). The chip draws as little as 238 μA in sleep mode. The SoC features an 32-bit Math Coprocessing Unit and Floating Point Unit, and boasts

210 Dhrystone Million Instructions per Second (DMIPS) performance. These are crucial features for allowing extensive on-board data processing. The 1 MB Flash internal read-only memory (ROM) and 192+4KB internal static random access memory (SRAM) also contribute to this. The sensor system hardware board has on-board memory, as well as a configurable secure digital input output (SDIO) interface for non-volatile Flash memory up to 32 gigabytes. I/O interfaces include RS-232, Ethernet and micro SD for sensors, data logging or interfaces to commercial data loggers; at the expense of additional power.

The processor can be programmed in the C programming language using a suitable programmer, such as Kiel's uVision 4 IDE™ and Kiel's uLink-ME™ programmer. The processor runs a Real Time Operating System (RTOS), specifically the RTX™ system from Kiel that administers the entire board. The board runs on a 12V power supply and can run at speeds up to 168 MHz. We are currently operating the processor at 32 or 64 MHz depending on the application.

A. Power/Operating Conditions

The microprocessor is powered by a 3.3V supply, and requires about 14-30 mA out of a total 150 mA for the entire RTU assembly for typical operation. The board is constructed to operate over an industrial temperature range: -40 °C to 85 °C. This wide temperature range is necessary for the extreme environments in our environmental monitoring applications. When the microprocessor goes to sleep, only flash memory and backup registers are retained. Finally, the microprocessor has 3 Analog to Digital Converters (ADCs) that allow for monitoring of battery voltage for the board power supply as well as monitoring of power levels for sensors with external power supplies.

The RTU has a 1 Watt radio implemented in either the 900 MHz ISM band, or with a separate design, at a licensed 414 MHz band for use at LANL. The radio is an Analog Devices ADF7021 with an HMC452ST89 external power amplifier and a Maxim 2634 low-noise pre-amplifier, with optional custom SAW filter, to meet our required range. The radio data rate is configurable. Lower data rates increase reliability in noisy RF environments such as the crowded ISM band. The radio is operating at 10417 bps. However, currently each data byte is encoded into 8 bytes for forward error correction so the real throughput is 1302 bps. Future work is to use 3-tone FSK that allows the use of the convolutional encode and Viterbi decode in the ADF7021. This will result in more efficient encoding without loss of performance. When fielded, we have several different antenna options. Primarily 3 foot, 5 foot or 8 foot omni-directional antennas are employed. The choice of antenna depends on the required antenna gain needed to successfully make the link to the remainder of the network.

The RTU can be configured to communicate via a serial port to a satellite modem. The modem may receive up to 270 bytes and transmit up to 340 bytes to a server per communication. This occurs in $\sim$10 microsecond transmission bursts, during that time the modem is transmitting at a power of 1.2 watts. It typically takes 1-2 minutes for the modem to acquire a satellite and complete communications before going back to sleep. Two-way communication enables remote updates of key parameters.

When limited to SBD messaging; on board compression of data, event detection, and event classification, can be essential, often combined with on-site data logging. Although communications are limited, processing power enables applications that require: triggering of other sensors, event response, or event logging for later retrieval of event data.

V. Performance

Measurements to study carbon flux from the Arctic tundra is a good example of the utility of power processing at the sensor. The raw data, collected from carbon flux sensors, is run through processing and averaging algorithms to calculate eddy covariance. First, de-spiking and interpolation is performed on the raw data. Next, covariance is computed for wind vectors, CO_2, H_20, temperature, and pressure. Then rotations are computed to account for sensor/tower orientation. Finally, Webb-Pearman-Leunning (WPL) corrections are used to compensate for fluctuations of temperature and water vapor. Performing this processing on the board allows for an 1800x compression on the size of the original data. Further, this raw binary data is compressed by 50% using Lempel-Ziv-Welch (LZW) compression.

RF performance was tested by a stormwater monitoring application at LANL (415 MHz). Nodes were deployed across rough terrain and in deep canyons preventing clear LOS. In some cases low gain omni-directional antennas were used to communicate a short distance to a relay node. Distances up to 19 km were achieved using an L-com HG409U 8.5 dBi omni antenna. Network performance is being logged with current and improved protocols and will be reported in a future paper.

Node power consumption is application dependent. The stormwater monitoring application is one extremal case. In this case each node is a member of a mesh network that must always be ready to detect new nodes and the board is always on consuming 348 mW. While transmitting, power consumption rises to 1.2 W, with each transmission lasting 10 microseconds. This transmission occurs about 300 times a day. This brings the average power consumption of the board in the stormwater runoff application to 408 mW. In the Arctic application the processor is at 32 MHz and only the processor and serial communication components are present (see Figure 3), the node is almost entirely in sleep mode using 23 mA. It wakes up, takes data, and transmits two

Figure 3. Image of the Arctic deployment with a datalogger and a SBD satellite modem, Abisko Station Sweden.

times per hour. The average power for the arctic application is 76 mW.

VI. Conclusions

The sensor network that we present in this paper is unique with regard to its combination of long distance links, high node count, low power, computational potential and application versatility. Though many of the previous efforts demonstrate some of these qualities individually, to our knowledge there is no published work detailing an RF self-healing mesh sensor network with node-to-node distances as large as 19 km and with a node count as large as 62 to 200 nodes. Additionally, our board's power consumption compares well to that of other long distance node systems.

Thus, RTU hardware system has key features that separate it from others. It 1) enables compression, processing and quality control of raw data prior to data transmission in a user-friendly C-based programming environment. 2) It has dual functionality for data transmission; a low power line-of-sight radio and satellite transmission 3) It uses a custom self-healing, self-forming mesh networking algorithm that enables networks to scale across unknown terrain and a degree of robustness in the field. 4) Any node in the network can function as a master, sensor or relay node implemented with the same hardware platform enabling a versatile, more compliant system.

A preliminary evaluation using a network of 62 nodes that was deployed using the RTU hardware last summer for the stormwater runoff project has shown that the system is able to successfully deliver event notifications over wide area multi hop self organizing networks with individual links as large as 19 km.

Our current plan is to extend the system to 200 nodes and collect detailed statistics about its scalability and robustness. The Arctic application highlight the low power sleep mode (76 mW) and the ability to process raw data at a 1800x saving in data reduction prior to transmission. The results of two field deployments show networks at high node count and long range (19 km) as well as in situ processing savings.

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